AEROTHERMODYNAMIC FLIGHT MEASUREMENT TECHNIQUES AND ENVIRONMENT ISSUES OF EXPERT
27 June – 1 July 2005, Anavyssos, Attica, Greece

H. Ottens[1], L.Walpot[1], J-M. Muylaert[2]

[1]AOES-Group B.V.,Haagse Schouwweg 6G, 2332 KG Leiden, The Netherlands,
Email:Harald.Ottens@AOES.com or Louis.Walpot@AOES.com
[2]ESA-ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands, Email:Jean-Marie.Muylaert@ESA.int

ABSTRACT

The paper reports on the aerothermodynamic (ATD) environment of the EXPERT configuration associated with the planned first flight (5km/sec trajectory). A status report is given on the embarked flight measurement technique developments and qualification with emphasis on the thermal protection system (TPS) integration issues. Special attention is given to the design of the flight measurement sensors themselves, their integration into the TPS as well as to the measurement of the free stream parameters during re-entry using an Air Data System (ADS). The paper will address the numerical design work to optimise the location of sensors in order to enhance the phenomena of interest, such as

- Definition of nose radius so as to avoid contamination of the boundary layer due to passive/active oxidation of the nose thermal protection system.
- Definition of the admissible step between nose and conical parts to avoid premature boundary layer transition
- Nonequilibrium maximum laminar heating on metallic PM1000 parts of the vehicle including effects of catalytic recombination validated through recent experiments in plasmatron.
- Turbulent reattachment of separated boundary layer on the flaps and in the vicinity of the corners of these flaps.

Today's status is that the preliminary design phase is completed and the preparations for the detailed design phase are ongoing.

INTRODUCTION

EXPERT is a demonstration vehicle that will perform a sub-orbital flight and re-enter the Earth atmosphere. The EXPERT vehicle will be equipped with state-of-the-art instrumentation and will provide flight measurements of critical aero-thermodynamic phenomena occurring during a hypersonic flight.

The objective of the EXPERT mission is to perform a sub orbital flight for in-flight measurements of critical aerothermodynamic phenomena using state-of-the-art instrumentation.

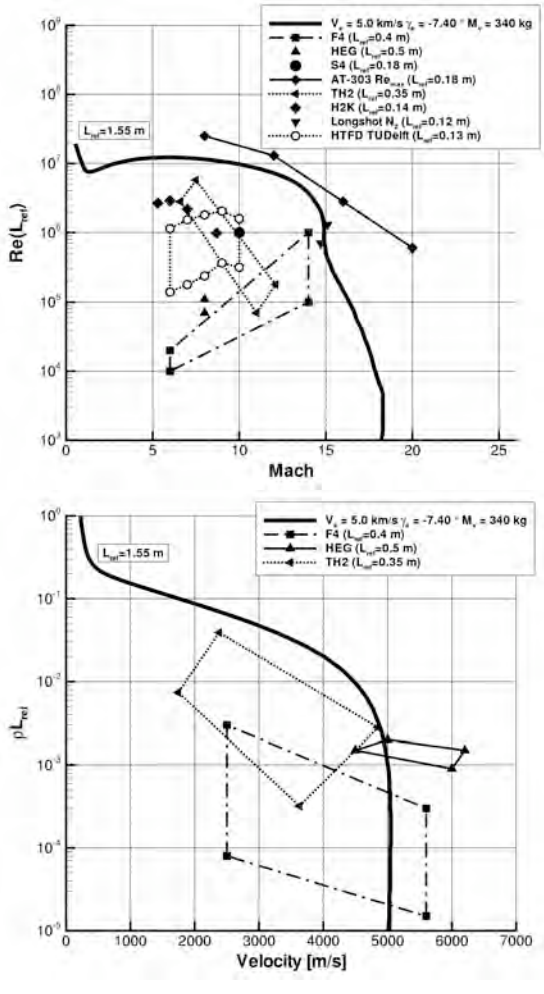

Fig. 1a and b: EXPERT trajectory with high-enthalpy facilities performance envelops.

Hypersonic flight data are required for improved understanding of the following critical ATD phenomena:

- Flap efficiency and heating
- Roughness induced boundary layer and shear layer transition

- Real gas effects on shock wave boundary layer interactions
- Micro-aerothermodynamics
- Shock layer chemistry
- Integration of sensors into surface, including free stream tracking using ADS

A test bed will be provided for validation of aerothermodynamics models, codes and ground test facilities in a representative flight environment, to improve the understanding of issues related to analysis, testing and extrapolation to flight. The measurements provided by the EXPERT mission will be used to study the wind tunnel-to-flight extrapolation at established high enthalpy facility and plasma facility crossing points (Fig. 1 a en b).

THE EXPERT VEHICLE

The EXPERT configuration has been redefined resulting in the current EXPERT 4.4 model, see Fig. 2. A body of revolution with an ellipse-clothoid-cone twodimensional longitudinal profile constitutes the shape.

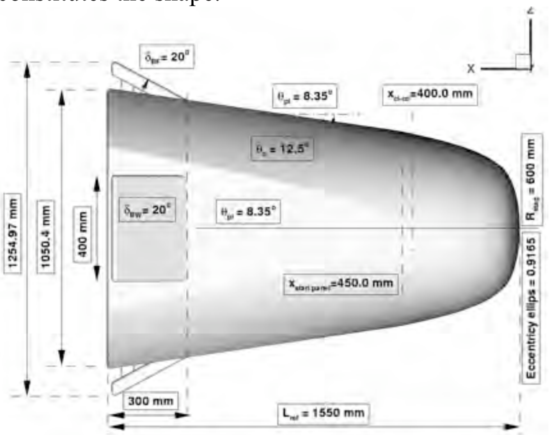

Fig. 2: EXPERT 4.4.b side view.

The nose is an ellipse with an eccentricity of 0.9165 with a local nose radius of 0.60 m. The ellipse- cone junction is second order by using a clothoid to avoid pressure jumps. The cone has an angle _$_{c}$=12.5° and features axisymmetric flow enabling two-dimensional sensitivity computations. The connection of the clothoid and the cone is located at x=0.40, exactly where the C-SiC ends and PM-1000 starts. So the C-SiC part covers completely the ellipse and the clothoid and the PM-1000 is just conical. The leading edge of the panels are located at x=0.45 m to avoid double curvature in the C-SiC part. The angle of the panels are _$_{pl}$=8.35°. The four flaps have a width of 0.40 m and a projected length of 0.30 m and their deflection angles _$_{bf}$ are 20°. Two flaps will be open (scoop) to study 3D micro-aerodynamic effects on corners, base flow recirculation and non convex reradiating wall effects. The length of the model is L_{ref}= 1.55 m. with a wetted base area S_{ref}=1.1877 m^2.

Fig. 3 addresses the influence of mass on stagnation heating. A partial catalytic wall has been assumed for the DLR C-SiC nose. It demonstrates that clean non-contaminated flight environment for detailed flight measurements are possible for a reentry speed of 5 km/s. The curve, describing the boundary of passive to active oxidation will be confirmed again with new detailed plasma facility tests. The figure includes also the theoretical and experimental analysis of Hilfer and recent DLR C-SiC experimental data on the boundary of passive/active oxidation obtained in the DLR L3K facility.

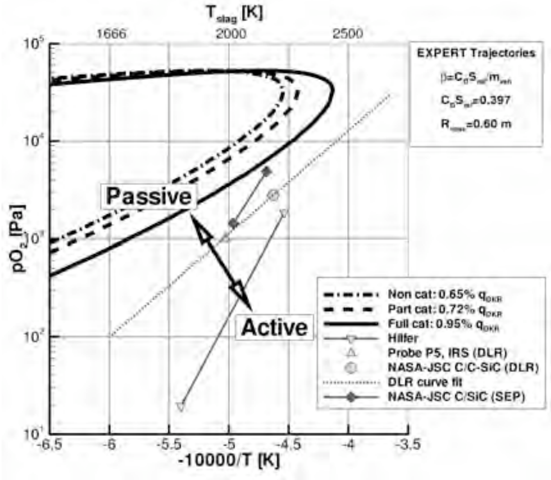

Fig. 3: EXPERT 5 km/s trajectory compared to passive/active oxidation criteria.

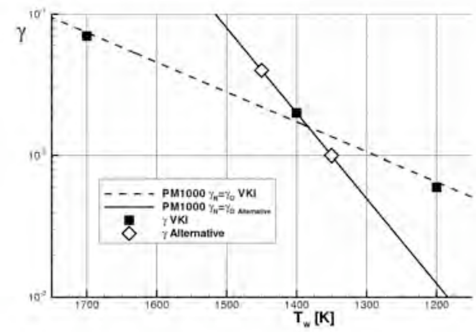

Fig. 4: Atomic recombination coefficients of Stewart and VKI measurements.

Nonequilibrium maximum laminar heating on metallic PM1000 parts of the vehicle including effects of catalytic recombination are performed. In this analysis a fixed wall temperature distribution is provided by DLR (including heat sink effect) and for the PM1000 a fixed temperature of 1450 K is used. The atomic recombination coefficients used for the computations are depicted in Fig. 4. Two curves/splines were included into the CFD code: a spline through the experiments obtained recombination coefficients and a line through the 4% γ at the junction and the 1% γ at the trailing edge referred to as "alternative". The computations are performed with Lore, a non-equilibrium Navier-Stokes solver with Park 1993 5-species chemistry model.

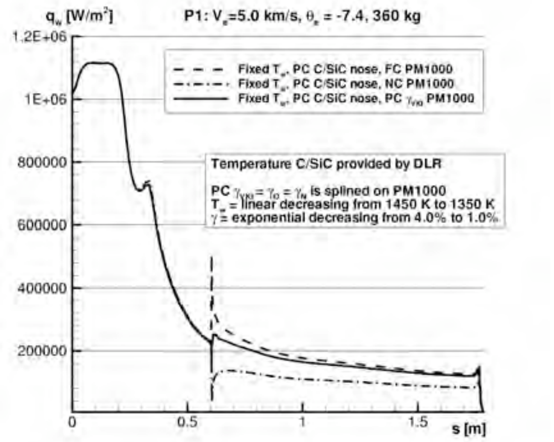

Fig. 5: Heat flux distribution using different PM1000 catalytic assumptions

Heat flux results are given in Fig. 5. The higher gamma at the junction results in a more catalytic PM1000 and therefore the heat flux is higher. The combination of a partial-catalytic C/SiC nose with a non-catalytic PM1000 shows a decrease in heat flux on the PM1000 while the full-catalytic PM1000 shows an overshoot. The partial-catalytic solution show only a small overshoot in heat flux on the PM1000 at the junction. Fig. 6 shows the temperature and heat flux distribution, the flaps are in radiative equilibrium.

THE SCIENTIFIC PAYLOADS

The EXPERT vehicle will carry state-of-the-art instrumentation for in-flight measurement of the critical aerothermodynamic phenomena: transition, catalysis, real gas effects on shock interaction, as well as blackout. Special attention will be paid to the design of measurement sensors, as well as to the measurement of the free-stream parameters during reentry.

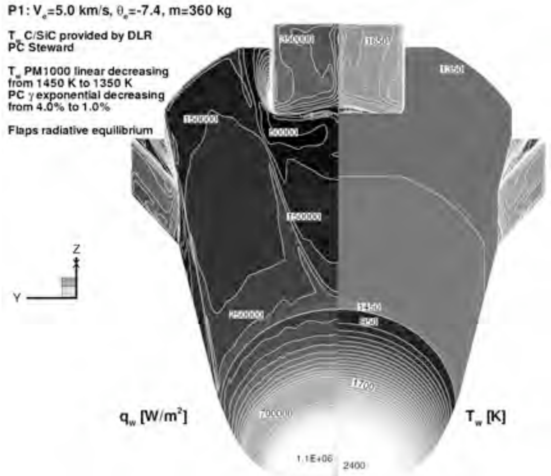

Fig. 6: 3D heat flux and wall temperature distribution.

Air Data System and Nose Heating

The nose of the vehicle, featuring high geometrical accuracy and a low surface catalicity, is designed to be an integration platform for both Flush Air Data System and heat flux sensors.

A pressure-based Air Data System (ADS) mounted on EXPERT's nose will provide free stream dynamic pressure, angle of attack and sideslip angle. Raflex gages are planned to be used as ADS sensors featuring combined pressure and heat flux measurements. These heat flux measurements will be compared with those obtained from the PYREX measurements.

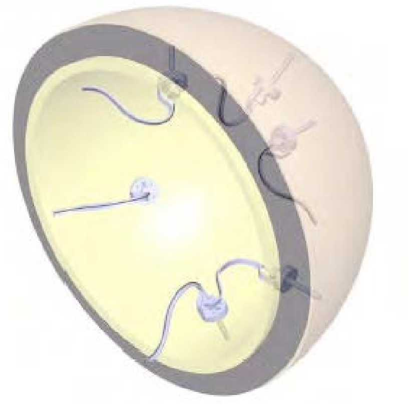

Fig. 7: Heat flux sensors mounted in nose

The goal of the latter payload (PYREX) is to determine the temperature history and corresponding heat fluxes at six locations on the nose (Fig. 7). Technology readiness is assured by the fact that EXPERT will take advantage of instrumentation originally developed for the X38 experimental vehicle to measure temperatures in the nose region

Roughness-induced transition

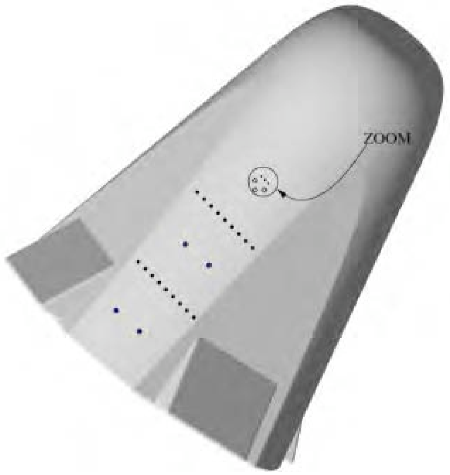

Fig. 8: Roughness elements on EXPERT

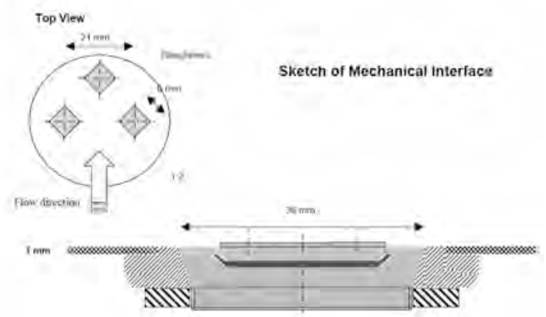

Fig. 9: Roughness elements in detail

Laminar to turbulent boundary-layer transition is considered one of the most critical aerothermodynamic phenomena due to the associated local temperature peaks and drag increase; unfortunately, present day hypersonic methods are based on old correlations that need to be revisited. In fact, chemistry effects are difficult to simulate in ground facilities and cold hypersonic facilities are affected by external disturbances (wind tunnel related), which constitute dominant sources of perturbations for transition triggering.

Thus, only flight experiments with well-characterized disturbances (triggering transition where required) may provide essential information to be coupled with ground facilities data and numerical simulation results. Roughness-inducing boundary-layer transition elements will be mounted on the leading edges of EXPERT in diametrically opposite locations. Their position, size and number will be chosen such that transition occurs in the lower altitude, higher Reynolds number part of the flight. Heat flux sensors will detect transition.

The remaining edges will be kept smooth in order to have a reference clean condition to be compared against the induced transition behavior.
Fig. 8 and Fig. 9 show a typical roughness element layout, whereas Fig. 10 addresses typical roughness induced transition correlations, which need to be validated via new flight data.

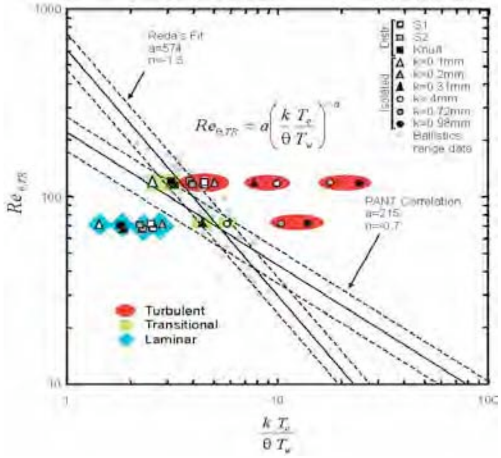

Fig. 10: Experimental activities on Roughness induced transition (courtesy VKI).

At this point, the importance of analyzing smooth surfaces has to be remarked: in fact, the experiment will be successful only if no transition is triggered by surface discontinuities upstream where the roughness elements are located. That is why this Payload addresses both surface discontinuities triggered transition and roughness element induced transition via CFD + stability analysis, wind tunnel test campaigns and flight tests.

Shock interactions around open flaps

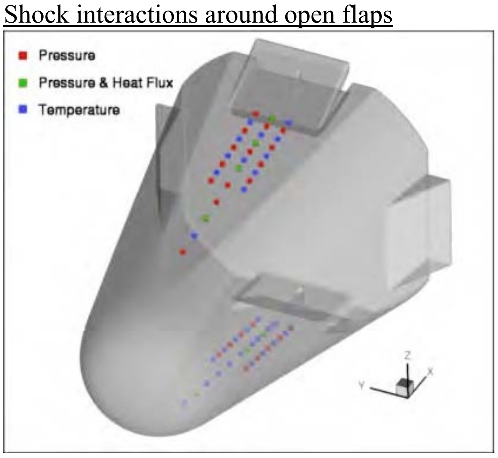

Fig. 11: Sensors located before the Open Flaps

Boundary-layer separation effects in front of a deflected flap (Fig. 11) affect not only the flap for control purposes, but also the heating associated with shear-layer reattachment. Three dimensional effects, corner and gap heating, base-flow circulation and wall cooling are all critical issues that need to be addressed in the design of control flaps. The set-up proposed for EXPERT consists of a space-vehicle ceramic flap with fixed actuator instrumented with simple but reliable devices such as thermocouples, heat and pressure gages, strain gages and micro-pyrometers.

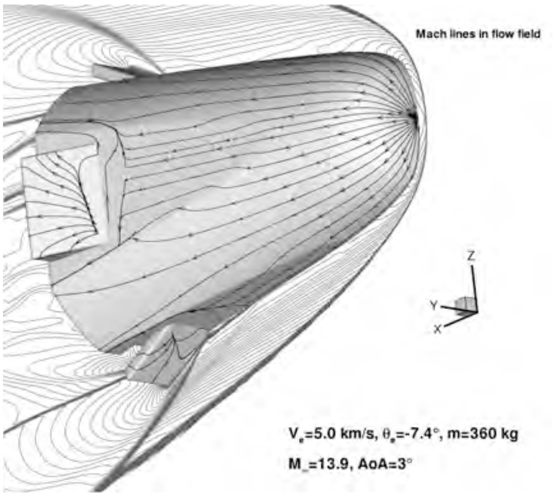

Fig. 12: Streamlines and Mach lines around EXPERT

In order to derive extrapolation-to-flight criteria able to reproduce both the mechanical and thermal loads acting on the control surface, a number of experimental tests will be performed. The EXPERT flight conditions in the flap region will be characterized by means of CFD and ground experimental activities. Also the flat faces upstream the flap are foreseen to be instrumented.

Heat fluxes inside closed flaps

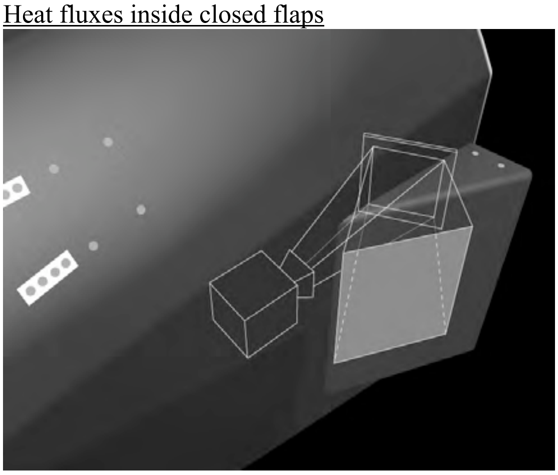

Fig. 13: Infrared camera in closed flap

The two closed flaps will be instrumented to measure accurately temperature and pressure in the reattached flow region and heat fluxes on the rear face. In particular one flap will feature unconventional measurement techniques, whereas an array of conventional sensors will be mounted on the opposite side for calibration and comparison.

To assess the location of the reattachment line with good accuracy, temperature sensitive paint will be used. The paint is foreseen to cover a sapphire window imbedded in the C/SiC flap.

Taking advantage of today's capabilities for measuring time-dependent 3D phenomena using non-intrusive techniques, an infrared camera (Fig. 13) will be mounted inside the closed flaps. Inverse methods will be applied to the data measured beneath the flaps in order to 'reconstruct' the external 3D heat flux during re-entry. As the deflection of all four flaps is identical, the flow results can be crosschecked with those predicted using the more classical methods.

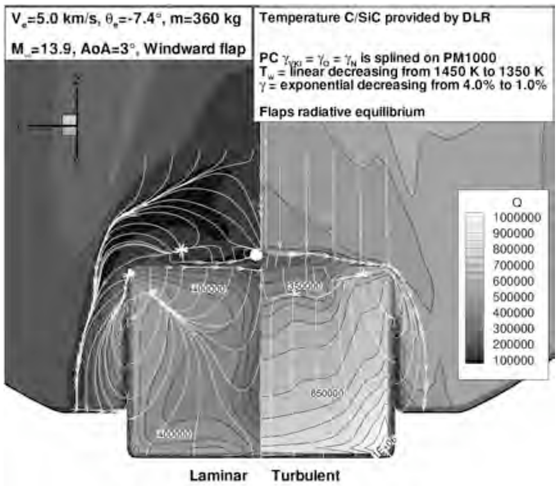

Fig. 14: Laminar and turbulent heat flux and separation bubble.

The laminar and turbulent heat flux distribution on and around the leeward and windward flaps are presented in Fig. 14. The heat flux on the corner of the windward flap reached 1.0 MW/m^2. The separation bubble is visualized with streamlines. The laminar bubbles are off course much larger. Care should be taken as it is known that a laminar separation combined with a turbulent reattachment provides a design case in which a transitional reattachment provides a higher heat flux than a fully turbulent case. The laminar flow show a much more complicated separated flow field then the turbulent flow, e.g. notice the secondary separation bubble.

Shock-layer chemistry-RESPECT

This instrument aims at collecting spectroscopic information during re-entry through spectrally resolved emission; the experimental data will then be compared with coupled flow field/radiation codes leading to the validation of used thermo-chemical models. The RESPECT subsystem (Fig. 15 shows a two channel device) consists of a miniaturized spectrometer, optical fibers and a lens system; the foreseen spectral range is 200-800 nm.

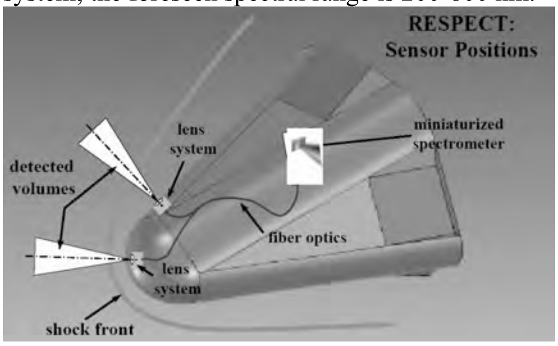

Fig. 15: RESPECT mounted on EXPERT (courtesy IRS)

The challenge of this flight instrument lies in the design of the electronics supporting the spectral measurement and the optical window through the heat shield. Preliminary activities performed at IRS demonstrated the feasibility of such a procedure.

Base flow measurements
This Payload aims at measuring steady and unsteady loads on the base of the vehicle. Local base pressure and heat flux measurements will be made to study the complex base recirculation flow in between the flaps.

Skin Friction Measurements
A slip flow sensor is foreseen to be integrated in the EXPERT vehicle: this combined probe mainly designed for surface flow diagnostics in the slip- and rarefied flow regimes may also be used in the laminar continuum flow regime. In the rarefied flow regime heat flux, particle flux to surface and slip speed ratio will be measured and surface pressure, heat flux and skin friction during the continuum regime.

The slip flow sensor has been designed with two inclined pressure taps, which are integrated in one caloric copper sensor head, ensuring same temperature for the cavities of both probes.

Sharp Hot Structures
The objective of this payload is to fly an instrumented patch of UHTC material. The payload could be a bulk ceramic component or coated component (UHTC covered with anti-oxidation UHTC). The flight test aims at monitoring the thermal conditions of the structure. Two symmetric locations are foreseen for this Payload.
The UHTC could be integrated on dummy winglets, similar to the Pitot static rakes or on a small-deflected surface at trailing edge of the vehicle leading edge.

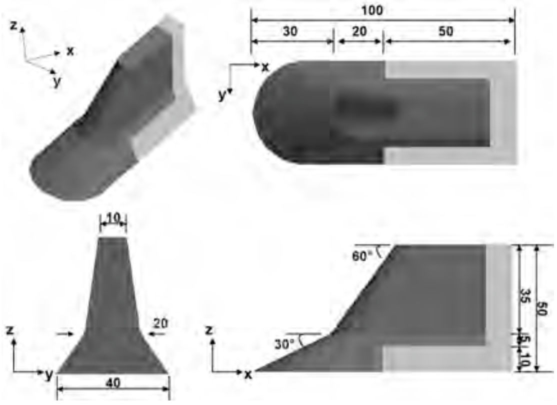

Fig. 16 Dimensions of the sharp hot structure

CONCLUSIONS

EXPERT is an in-flight research programme, with the objective to improve our understanding of critical aerothermodynamics phenomena such as transition, real gas effects and shock wave boundary layer interactions associated with flap efficiency and heating. At present one ballistic flight (5 km/sec) is planned. If successful, it is believed that other flights are possible such as for higher speed (6 km/sec); future flights for the study of transitional flow phenomena and skipping trajectories, jet interaction, demonstrator for MHD/nose heat flux reduction schemes and flights for the study of advanced materials associated with high-speed re-entry.

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